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Personalized three-dimensional printed coronary artery models for accurate assessment of coronary stenosis using high resolution imaging modality

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Editorial

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ABSTRACT

Three-dimensional (3D) printing shows great potential in the medical field with a wide range of clinical applications. 3D printed models based on patient's imaging data are reported to develop optimal visualization of coronary plaques and accurate assessment of coronary stenosis caused by extensive calcification. This editorial highlights the usefulness of personalized 3D printed coronary models for determination of coronary stenosis using high resolution synchrotron radiation technique. Ultra-high synchrotron radiation CT images were reconstructed with slice thicknesses between 0.095 and 0.491 mm to study the effect of different spatial resolutions on assessment of coronary stenosis. Intraluminal plaque appearances were also visualized and compared between different coronary CT protocols.

Key Words
Assessment, coronary artery disease, coronary plaque, model, three-dimensional printing, visualization

Implications for Practice:

1. What is known about this subject?
Coronary CT angiography is widely used as a less invasive modality in the diagnosis of coronary artery disease. However, when diagnosing calcified plaques it has low to moderate accuracy because of extensive calcification leading to high false positive rate.

2. What new information is offered in this case study?
Use of personalized 3D printed coronary models with calcified plaques inserted in the coronary arteries allows for accurate assessment of coronary stenosis. This editorial summarises our research experience of using personalized 3D printed coronary models for determination of effect of spatial resolution on plaque visualization and lumen assessment.

3. What are the implications for research, policy, or practice?
Personalized 3D printed coronary models can be used to develop optimal coronary CT protocols for visualization of coronary plaques and coronary lumen assessment in the presence of severe calcification.

Introduction

Coronary computed tomography angiography (CCTA) is a commonly used less-invasive modality in the diagnosis of coronary artery disease with high diagnostic value.[1-4] However, it has limited value in the visualization of calcified plaques because blooming and beam hardening artifacts could result in low specificity, thus compromising its diagnostic accuracy.[5-9]

This limitation has been addressed by a number of approaches including use of iterative reconstruction (IR) and image post-processing algorithms for reducing the negative impact of heavy calcification.[10-12] Another strategy is to use high resolution CT imaging such as spatial resolution of 0.23mm slice thickness as this has been shown to improve CCTA in the diagnostic assessment of calcified plaques.[13-15] This has been confirmed by our recent experiments using high resolution synchrotron radiation CT for assessing the coronary stenosis on three-dimensional (3D) printed coronary models. This editorial summarises some key findings from the experiments and highlights the potential of improving CCTA in diagnosing calcified plaques using high resolution imaging technique.

Quantitative Assessment of Coronary Stenosis Based on 3D Printed Coronary Models

Synchrotron radiation CT has resolution far superior to that of medical CT scanners, thus demonstrating advantages in accurate assessment of fine anatomical details, including stent wires or calcified plaques.[16-19] In this study, we fabricated 3D printed coronary models based on selected cases of CCTA angiography images.[19] Furthermore, calcification was printed and deployed into the models to create simulation of calcified plaques with resultant coronary lumen stenosis ranging from 50 to 90 per cent stenosis. The 3D models were printed using Polyjet 3D printer Stratasys' Objet 500 Connex 3 (Objective 3D, Melbourne, Victoria, Australia). Figure 1 shows the 3D printed coronary models used in the study. Calcified plaques can be visualized in the left coronary artery branches. The coronary arteries were printed with soft material, TangoPlus with property similar to that of arterial wall, while calcified plaques were printed with rigid material VeroWhite to simulate calcification. The 3D printed models were scanned with synchrotron radiation CT which is available at the Australian Synchrotron in Melbourne using the Imaging and Medical Beamline (IMBL). Images were originally scanned with very high resolution of 0.019mm (voxel size: $0.019 \times 0.019 \times 0.019 mm^3$), then they were further reconstructed with different slice thicknesses resulting in voxel size of $0.095 \times 0.095 \times 0.095$, $0.208 \times 0.208 \times 0.208$, $0.302 \times 0.302 \times 0.302$, and $0.491 \times 0.491 \times 0.491 mm^3$. Results showed that high resolution 2D and 3D images reconstructed with slice thicknesses between 0.095 and 0.302mm detected coronary stenosis with findings similar to the actual stenosis. In contrast, when synchrotron radiation CT images were reconstructed with a slice thickness of 0.491mm, coronary stenosis was overestimated significantly due to inferior spatial resolution, thus compromising visualization of coronary plaques and assessment of lumen stenosis (Figures 2 and 3). Furthermore, images acquired with the beam energy of 30 keV produced the best visualization of coronary lumen and plaque appearances when compared to those with 40 and 50 keV.[19]

This study further highlights the impact of spatial resolution on the visualization of calcified plaques and associated lumen stenosis. CCTA is routinely used in clinical practice for the diagnostic assessment of coronary artery disease owing to improvements in imaging techniques that are available with the latest CT scanners, despite presence of high heart rates.[3,4] However, presence of heavy calcifications still presents a challenge for CCTA since blooming or beam hardening artifacts significantly affect its specificity and positive predictive value. A recent study reported that use of de-blooming algorithm in CCTA image reconstruction is another new approach which increased specificity from 45.8 per cent and 62.5 per cent to 75 per cent and 83.3 per cent in the diagnosis of significant coronary stenosis caused by calcified plaques (Figure 4). Authors also showed the improved visualization of coronary lumen and detection of coronary stenosis in images reconstructed with high-definition standard kernel compared to those reconstructed with the standard kernel.[20] Although these strategies are effective for reducing the effect of blooming artifacts on calcified plaques to some extent, beam hardening artifacts resulting from highly calcified plaques remain unchanged because of inferior spatial resolution that is inherent in the present CT scanners.

The latest CT prototype enables acquisition of high resolution images with slice thickness between 0.23 and 0.25mm, thus improving diagnostic value of CCTA for detecting coronary stenosis and coronary stents when comparted to conventional resolution CT (0.23/0.25mm *vs.* 0.5/0.625mm slice thickness).[13,15,21] Figure 5 shows that images of 3D printed coronary models acquired with high resolution of 0.23mm provide better delineation of coronary artery and plaques than those acquired with 0.5mm slice thickness. Results of our recent study using synchrotron radiation CT support these findings.[19] Synchrotron radiation CT offers excellent spatial resolution which is more than 10-fold of latest CT scanners. The imaging data in the experiments were originally acquired with slice thickness of 0.019mm, and images were reconstructed with different slice thicknesses similar to those available with current CT scanners in the clinical practice. 2D and 3D visualizations and assessments of coronary stenosis were found more accurate with images reconstructed with slice thicknesses between 0.095 and 0.302mm when compared to those with a slice thickness of 0.491mm (Figures 2 and 3). This further confirms the value of high resolution CCTA in diagnosing calcified plaques, and suggests the future direction of CCTA in coronary imaging.

Summary and Conclusion

Personalized 3D printed coronary models with coronary plaques can be used to develop optimal coronary CT angiography protocols for the purpose of providing more accurate assessment of coronary stenosis, despite presence of heavy calcification. These realistic 3D printed coronary models can also be used to simulate coronary stenting with insertion of different sizes of stents, therefore, assisting development of optimal CT protocols for accurate detection of in-stent restenosis.

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PEER REVIEW

Peer reviewed.

CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

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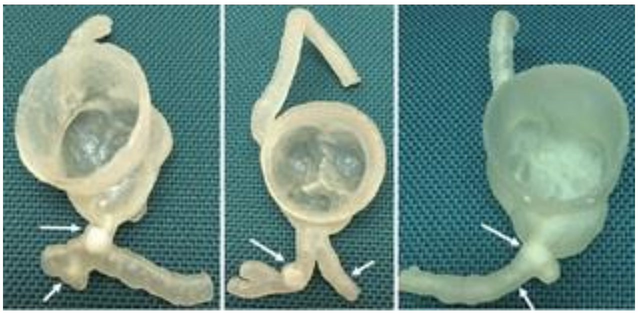
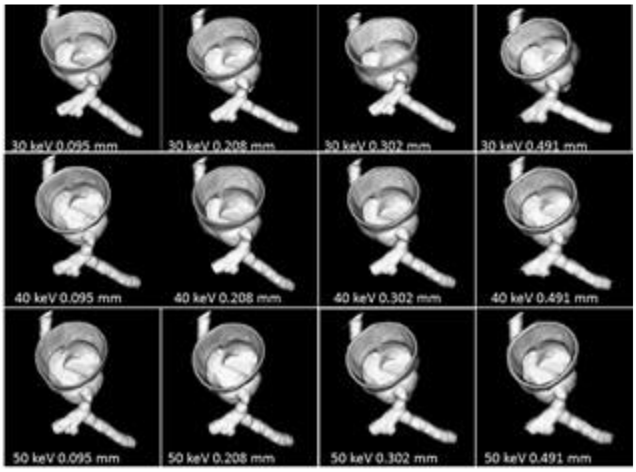
Figure 1: 3D printed coronary models with calcified plaques in the left coronary arteries



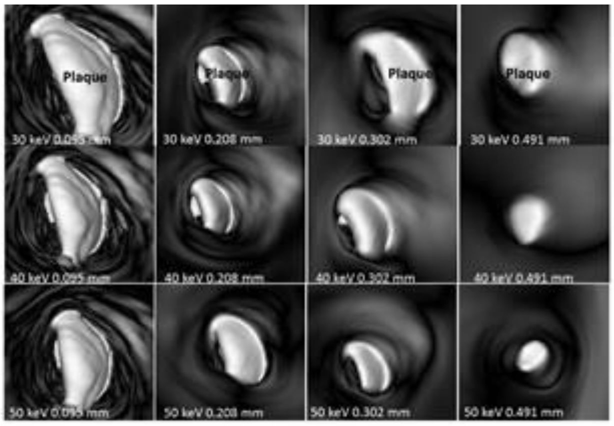
Calcified plaques were seen in the left main stem (LM) and left anterior descending (LAD) in model 1 (left image), LAD and left circumflex (LCx) in model 2 (middle image), and LAD in model 3 (right image). Long arrows refers to the calcification in the LM and LAD with more than 80 per cent stenosis, while short arrows refer to the calcification in the LAD and LCx with 50–70 per cent stenosis. Reprinted with permission from Sun et al.[19]

Figure 2: 3D synchrotron radiation CT visualization of model 1



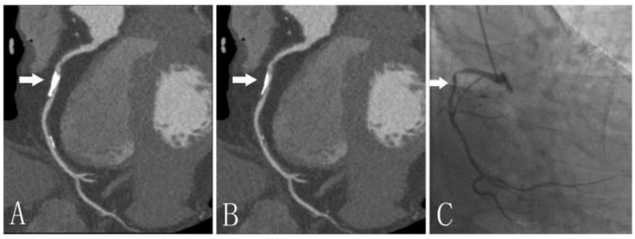
The 3D printed model was scanned with synchrotron radiation CT with beam energies between 30 and 50keV and slice thicknesses between 0.095 and 0.491mm. Visualization of coronary wall and plaques is suboptimal when the slice thickness is increased to 0.491mm. Reprinted with permission from Sun et al.[19]

Figure 3: 3D virtual intravascular endoscopy (VIE) visualization of coronary plaque of model 2



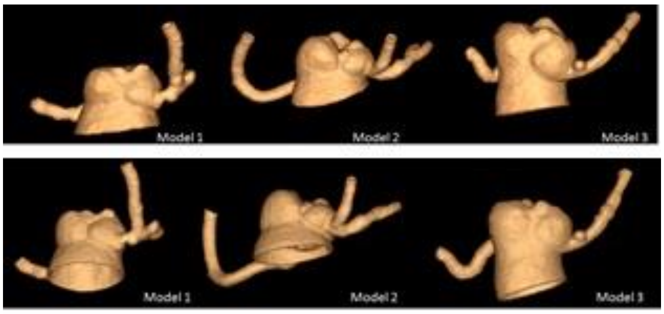
Synchrotron radiation CT images were acquired with beam energies between 30 and 50keV and slice thicknesses ranging from 0.095 to 0.491mm. 3D VIE images clearly show the intraluminal appearance of coronary plaque with images reconstructed at slice thicknesses between 0.095 and 0.302mm. The plaque becomes irregular when the slice thickness is increased to 0.491mm. Reprinted with permission from Sun et al.[19]

Figure 4: Effect of calcified plaque (arrows) on coronary lumen visualization



Curved planar reformation images of a 77-year-old patient diagnosed with coronary artery disease in the right coronary artery. (A): coronary lumen seems to be occluded on coronary CT image without using de-blooming algorithm. (B): with use of de-blooming algorithm the volume of calcified plaque was reduced and the lumen evaluation was improved when compared to image in A. (C): The stenosis in the right coronary artery was confirmed to be moderate by invasive coronary angiography. Reprinted with permission under the open access from Li et al.[20]

Figure 5: 3D reconstructions of 3D printed coronary models with images acquired with different resolutions



Top row images: Images were scanned on a 192-slice Siemens Force CT scanner with slice thickness of 0.5mm. Bottom row images: images were scanned on a 256-slice GE Revolution CT scanner with slice thickness of 0.23mm. 3D reconstructions of these coronary models with high resolution images (0.23mm) show improved visualization of coronary lumen and plaques when compared to the standard resolution images (0.5mm).